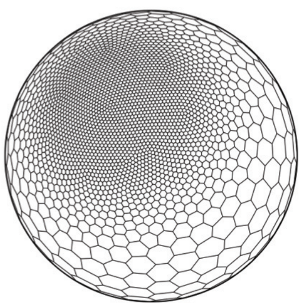
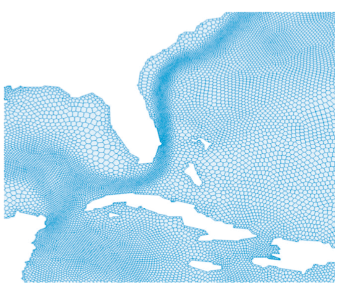
Improved Performance of MPAS-Ocean, an Unstructured-grid Ocean-Climate Model

Mark R. Petersen, CCS-2; Todd D. Ringler, Douglas W. Jacobsen, Mathew E. Maltrud, Philip W. Jones, T-3

The Model for Prediction Across Scales-Ocean (MPAS-Ocean) is a new ocean model being developed for global climate change studies. MPAS-Ocean uses unstructured horizontal grids that enable it to perform high-resolution regional simulations within low-resolution global grids, with smoothly varying grid transitions. Major accomplishments this year include a split explicit time-stepping algorithm that improves performance by a factor of 12, automated performance testing, high-order horizontal and vertical advection, implicit vertical mixing, and an Arbitrary Lagrangian-Eulerian (ALE) vertical coordinate. MPAS-Ocean is now a fully functioning ocean model, and successful simulations have been run on realistic global quasi-uniform grids, variable resolution global grids down to 10-km gridcells, and a number of idealized test cases.

Fig. 1. Sample MPAS-Ocean unstructured grids. With MPAS, users have a great deal of freedom to specify mesh density, so computational resources can be spent where they are most needed.





In order to prepare a new climate model component for public release and use in century-long climate-change simulations, there are several requirements that must be satisfied. The model must be well-documented and easy to run, standard parameterizations for vertical and horizontal mixing must be included, and the model must be validated against trusted metrics. In the end, however, a new climate-model component must be computationally efficient to be widely adopted by the community.

The Model of Prediction Across Scales-Ocean (MPAS-Ocean) is a new ocean-climate model developed by the Climate, Ocean, and Sea Ice Modeling (COSIM) team at LANL. It uses horizontally unstructured grids, so that high-resolution regions may be embedded within a lower-resolution global grid (Fig. 1). This is useful for climate-change studies of a particular region while capturing global processes that influence the area in question. The global meshes, created using Spherical Centroidal Voronoi Tesselations [1], vary smoothly from low- to high-resolution regions. The same algorithms and in fact, the same code, are used in all gridcells. This stands in contrast to traditional regional models, which use many nested uniform grids with sharp transitions in resolution, and even use separate models for these different regions. Important conservation properties for mass, tracers, potential vorticity, and energy are maintained, even when using variable resolution meshes [2,3]. The underlying scheme when paired with variable resolution meshes was also evaluated with encouraging results in 2011 [4].

MPAS is part of a collaborative effort between LANL and the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, to create earth system model components for unstructured grids. The MPAS framework includes ocean, hydrostatic and nonhydrostatic atmosphere, and shallow water components and plans are in place for sea ice and land ice components.

The major effort with MPAS-Ocean in 2011 focused on improving model performance. Development of MPAS-Ocean began in 2010, and by year's end it was a functioning ocean dynamical core that could run globally with land boundaries and topography. However, the Runge-Kutta time-stepping algorithm in place at that time was too slow to be a viable method for climate change simulations. The solution was to advance to a split time-stepping scheme, which improved performance by a factor of 12.

The newly implemented time-stepping algorithm in MPAS-Ocean is a split explicit barotropic/baroclinic scheme. In ocean models, the time step is severely restricted by the fast surface gravity waves, which travel at ~200 m/s, while the next time-step limitation is imposed by slow internal gravity waves at 1–2 m/s. The surface wave dynamics may be solved efficiently using 2D barotropic (vertically integrated) equations at a small time step, while the remaining 3D baroclinic system, now free of surface waves, may take a large time step. In practice, the barotropic system is subcycled within each baroclinic time step. The whole process is repeated within a predictor-corrector scheme, and each stage includes individual iterations. In the end, there were many degrees of freedom to optimize in order to obtain a stable and efficient algorithm.

Many other additions were made to MPAS-Ocean to improve performance. The code was optimized by fusing loops and replacing branches with masks within loops, resulting in a 10% speed-up. The code was modularized to improve organization and readability, and new timers provide detailed performance profiles. Scripts were used to automate performance testing so that modifications could be

For more information contact Mark R. Petersen at mpetersen@lanl.gov

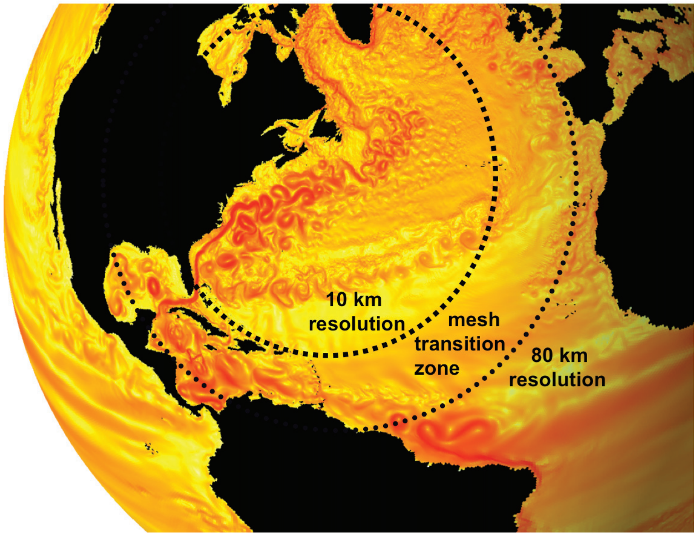


Fig. 2. Surface kinetic energy from a global, real-bathymetry simulation. The mesh density varies smoothly from 80 km over most of the globe, to 10 km in the North Atlantic. Significant eddy activity is visible in the high-resolution region.

incrementally tested for speed and accuracy over a variety of test configurations.

Performance tests using realistic global domains show excellent scaling out to thousands of processors and from resolutions of 120-km to 15-km gridcells. The progression from the Runge-Kutta time-stepping to the split explicit time-stepping shows a 12-fold speed-up. These tests were performed on Lobo, an Institutional Computing resource at LANL.

POP, the Parallel Ocean Program, is an ocean-climate model developed and maintained by the COSIM team since 1992. It has been used extensively for climate-change simulations that are published in the Intergovernmental Panel on Climate Change (IPCC), and so is a good comparison for MPAS-Ocean performance. MPAS-Ocean is currently 1.9 times slower than POP at lower resolution, and 3.4 times slower at higher resolution (compare the blue and red lines on Fig. 2). POP runs on structured rectangular grids, so it has the advantage that horizontal neighbors are brought into local memory in the same fetch. MPAS-Ocean's unstructured grid means that horizontal neighbors are accessed through pointers, and may not be nearby in memory. To compensate for this, MPAS-Ocean orders tracers and vertical neighbors first in memory, and does not include land gridcells.

Considering that POP has been scrutinized for performance improvement for the last 20 years and MPAS-Ocean uses completely different data structures and time splitting, we feel that a factor of 1.9-3.4 in speed between POP and MPAS-Ocean is a major accomplishment. We are confident that MPAS-Ocean performance can be improved even further. The number of messages passed among CPUs can be reduced by packaging many variables into a single message, and using very wide halos in the barotropic variables that are explicitly subcyled. Tracers and density may be updated less frequently than the dynamic variables with little loss in accuracy.

There have been many accomplishments in MPAS-Ocean development in 2011 other than performance. High-order horizontal and vertical advection has been added for accurate tracer transport. Richardson-number-based vertical mixing and implicit vertical mixing are required so that vertical diffusion increases in less stratified conditions, and so the time step is not restricted when high vertical diffusion is required. We have implemented an Arbitrary Lagrangian-Eulerian (ALE), or generalized vertical coordinate, so that vertical gridcell interfaces oscillate with changes in sea-surface height, reducing spurious vertical mixing between layers.

Global simulations are now in progress using high-resolution quasi-uniform meshes and variable-resolution meshes. Figure 2 shows results from a North Atlantic regional variable-resolution mesh, where significant eddy activity can be seen in the Gulf Stream within the 10-km resolution region. The low-resolution 80-km region does not resolve eddies, but provides global currents that drive the North Atlantic region of interest.

In the coming year, we plan to introduce MPAS-Ocean to the ocean modeling community in several publications, and couple MPAS-Ocean to the Community Earth System Model (CESM) to run earth-climate simulations that include a dynamic atmosphere, sea ice, and land surface. A longer-term research goal is to develop "scale-aware" parameterizations for horizontal mixing that work well on variable resolution meshes without the need for tuning of coefficients on each new grid.

[1] Ringler, T. et al., *Ocean Dynam* **58**, 475 (2008).
[2] Thubern, J. et al., *J Comput Phys* **228**, 8321 (2009).
[3] Ringler, T. et al., *J Comput Phys* **229**, 3065 (2010).[4] Ringler, T. et al., *Mon Weather Rev* **139**, 3348 (2011).

Funding Acknowledgments
DOE Office of Science, Biological and Environmental Research, Climate Change Prediction Program, Climate and Earth Systems Modeling